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Buzzes and High-Frequency Clicks Recorded from Narwhals (*Monodon monoceros*) at Their Wintering Ground

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Abstract

High-frequency broadband clicks were recorded from narwhals (*Monodon monoceros*) off the Uummannaq region, Northwest Greenland, in April 2012 and 2013 while whales were on their wintering grounds in Baffin Bay. Recordings were made on eight different days directly from the pack ice edge or through holes drilled in pack ice floes at approximately 71° N and between 54° to 60° W. Recordings were conducted using a single hydrophone along with a recording system with a sampling frequency of 500 kHz and an Acousonde™ 3B with a sampling frequency of 250 kHz. The energy in the high-frequency narwhal clicks extended up to 200 kHz. Buzzes with inter-click intervals (ICI) down to 3.2 ms were also recorded; however, no whistles were obtained. This is the first time the whole bandwidth of narwhal echolocation clicks has been reported and the first case for which buzzes have been recorded from narwhals at their wintering ground. These data may have implications for conservation, management, and acoustic monitoring techniques in light of ongoing and expected significant increases in anthropogenic sound (e.g., seismic exploration, shipping) in the Arctic.

Key Words: narwhals, *Monodon monoceros*, clicks, echolocation, foraging

Introduction

Narwhals (*Monodon monoceros*) are toothed whales endemic to the Arctic waters that occur year-round in West and East Greenland (Heide-Jørgensen et al., 2002, 2010). Narwhals are one of two members of the family Monodontidae together with the beluga (*Delphinapterus leucas*). Males can grow slightly larger than females and may reach 4.7 m in length and 1.6 tons, while fully grown females attain a length of 4 m and 0.9 tons (Mansfield et al., 1975).

In West Greenland and Canada, narwhals make long annual migrations. They spend the summer in coastal high Arctic areas and migrate offshore during the fall where they overwinter in deep ice-covered waters in central Baffin and Davis Strait (Dietz & Heide-Jørgensen, 1995; Dietz et al., 2001; Heide-Jørgensen et al., 2002, 2003). During the winter, the narwhals may feed on the Greenland halibut (*Reinhardtius hippoglossoides*) and squid (*Gonatus fabricii*), or in some areas on pelagic fish (Laidre & Heide-Jørgensen, 2005; Watt et al., 2013).

The first sound recordings of narwhals were made by Watkins et al. (1971), who described the click and whistle sounds, and reported sound containing frequencies up to 24 kHz. Later, Ford & Fischer (1978) described the sound repertoire used by narwhals as pulsed and pure tone vocalizations, containing frequencies up to 24 kHz. Miller et al. (1995) described the click characteristics and click intervals of narwhals using a system with a frequency response of 100 Hz to 125 kHz (± 2 dB) and divided the click sequences into click trains and click bursts. Click trains were emitted with inter-click intervals (ICI) of 33 to 500 ms, while click bursts were emitted with 2.5 to 25 ms.

Møhl et al. (1990) calculated source levels of narwhal clicks, and the range varied from 209 dB to 227 dB pp re 1 μPa. Other more recent studies have used audio sound recording systems with a frequency response up to 30 kHz (Marcoux et al., 2012) or sampling frequency of 96 kHz (Shapiro, 2006; Stafford et al., 2011). In general, sounds have been divided into whistles, pulsed calls, and clicks. While these studies have collected valuable data, they were restricted by *a priori* sampling decisions or the limitations of sampling equipment.

The purpose of this study was to document the entire frequency range used by narwhals by sampling with 500 kHz in the offshore winter pack ice of Baffin Bay where intensive feeding is known to take place. We describe the whole frequency range used by narwhals and compare our findings to recent findings for other toothed whale species.

Methods

The fieldwork was conducted between 19 March and 2 April 2012 and 19 March and 1 April 2013 based out of a field station in Niaqornat, West Greenland. On clear weather days, an AS350 helicopter was flown 100 to 150 km offshore in the pack ice using strategically placed fuel depots. Observers searched for narwhals in the vicinity of the leads and cracks; and when whales were spotted, the helicopter landed on the sea ice. Equipment was deployed from either the ice edge or by creating a hole with a drill in a large ice floe in close proximity to open water. Narwhals were visually observed during all recordings within a maximum distance of 1 km; and no other cetaceans were sighted in the dense pack ice. In both years, the recording systems were at depths between 50 and 250 m. Average air temperatures were -20° C, and sea ice was > 98% concentration.

Sound recordings were made on eight different sampling days between 22 March and 1 April 2012 and on two recording days in March 2013 (23 and 29 March). Two recording systems were used. The first consisted of a Reson TC4014 (Linear frequency range 25 Hz to 250 kHz ± 3 dB) with 100 m of cable connected to an Etec A2002 hydrophone amplifier with high pass filter at 1 Hz to low pass filter at 300 kHz (2nd order filter). The hydrophone amplifier was connected to a NI-USB-6341 using a sample rate of 500 kHz and connected to a General Dynamics 8,000 robust laptop computer. The pre-amplifier and laptop were encased in a portable heated aluminum box (Zarges) and powered with a 12-V marine battery. Custom-designed recording software written in *LabView* (Alain Moriat, NI, Denmark) was used to collect data. The other recording system consisted of a single Acousonde™ 3B (Cetacean Research Technology) lowered under water with a winch. This system used a sample rate of 250 and 232 kHz, and recording depth varied between 50 and 250 m.

Sound analysing was conducted using *Cool Edit Pro* (Adobe *Audition*), *BatSound* (Petterson, electronics), *Raven Pro 1.4* (Cornell Lab of Ornithology), and *SigPro* (Simon Boel Pedersen). Frequency analyses were only done on recordings using the Reson hydrophone and sample rate of 500 kHz due to limitations in the sample rate with the Acousonde™ (sample rate of 232 or 250 kHz). From visual inspection of individual clicks, only those with high amplitude with few cycles were analysed along with inspection of recordings from the center hydrophone compared to outer hydrophones (as in Rasmussen et al., 2002; Au & Herzing, 2003), and these clicks were selected as on-axis (not off-axis) clicks. Durations of single clicks were calculated using a custom-written software (*SigPro*) and energy bandwidth, and centroid frequency was estimated using *Raven Pro*. Peak frequency and 3- and 10-dB bandwidths were measured using *BatSound*. Click intervals were mostly calculated from sequences where only one narwhal was echolocating. Click sequences and clicks were visually inspected using Adobe *Audition* and *BatSound*. The recordings from the Acousonde™ 3B were only used to investigate ICI buzzes (click sequences with high repetition rate) and not used for description of the properties of the clicks. Buzz clicks or burst-pulse signals were defined as in Lammers et al. (2003) starting with short ICI (< 10 ms) and ending with a very short ICI (< 3) ms. The spectra and plots were computerized using *Matlab*, Version 2014a.

Results

All narwhals were sighted and recorded in the offshore area at approximately 70 to 71° N and between 54° to 60° W (Figure 1). Table I summarizes all the recording events and locations. In 2012, 915 min were recorded with the Reson hydrophone, and 379 min were recorded with the Acousonde™ (Table 1A). In 2013, 46 min were recorded with the Reson hydrophone (Table 1B) for a total of 1,340 min recorded over the 2-y period.

Narwhals were < 1 km from the recording sites, and group size varied between 5 and 25 animals when the recordings were made. Clicks were recorded, including both click and buzz sequences with high repetition rate, but no whistles or other communication sounds were obtained. The energy in the high-frequency narwhal clicks extended well above 100 kHz (Table 2), and they were very broadband with an average 10-dB bandwidth of 52 ± 11 kHz (N = 300). Peak frequencies varied between 55 and 83 kHz (mean 69 ± 14 kHz) (N = 300). Figures 2 & 3 show an example of waveforms from 34 single clicks and the power spectra of all 34 high-frequency broadband clicks.

We also recorded both possible search click and buzz sequences. In our study, buzzes were described as clicks with an ICI of 200 ms in slow rate, then intervals decreasing down to a minimum of ICI of 4.2 or 3.2 ms in the buzz phase (Figures 4 & 5). An example of a buzz sequence recorded with the Reson system is shown in Figure 4. In this example,

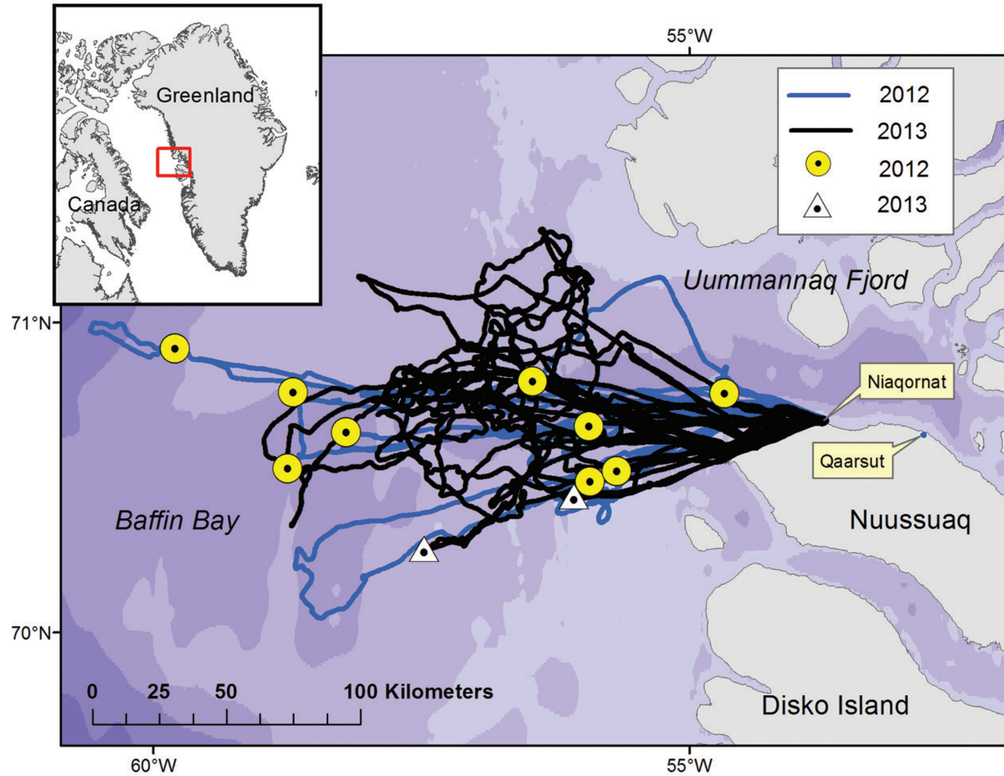

Figure 1. Map of the study area in Greenland, including the location of the recording site (see inset). The map shows search effort in 2012 (blue lines) and 2013 (black lines). The circles represent recording locations in 2012, and the triangles represent recording locations in 2013.

the minimum ICI is 4.2 ms. Animation recorded for this shows the same buzz sequence as shown in this figure recorded with the Reson hydrophone (see video clip posted on the *Aquatic Mammals* website: www.aquaticmammalsjournal.org/index.php?option=com_content&view=article&id=10&Itemid=147). The amplitude and frequency content changes as the animal presumably scans over the hydrophone. Another buzz example recorded with the Acousonde™ is shown in Figure 5. The minimum ICI during the buzz is 3.2 ms.

Discussion

This is the first description of high-frequency clicks from narwhals (Figure 3) and the first characterization of the entire bandwidth of echolocation clicks for this species. The clicks contain frequencies above 150 kHz and are similar to broadband clicks recorded from white-beaked dolphins (*Lagenorhynchus albirostris*) (Rasmussen & Miller, 2002) and as seen on the power spectra from bottlenose dolphins (*Tursiops aduncus*) in Wahlberg et al. (2011). For example, at 150 kHz, the amplitude is about 10 dB below the amplitude at the peak frequency. Frequencies this high have not been described previously for narwhals either due to the limitations of recording equipment or *a priori* sampling decisions. Marcoux et al. (2012) were able to describe spectral content with frequencies up to 30 kHz; and Stafford et al. (2011) described them up to 48 kHz, while Miller et al. (1995) were able to analyse frequencies up to 125 kHz. Other reasons may be the directionality of echolocation signals (Rasmussen et al., 2002, 2004; Au & Herzing, 2003). Concerning the 10-dB beamwidth, for bottlenose dolphins (*T. truncatus*), Au (1980) measured it as 22°, and for *T. aduncus* in Australian waters, Wahlberg et al. (2011) reported a 10° measurement, similar to what has been seen in white-beaked dolphins (Rasmussen et al., 2004). The -3-dB beamwidth in the horizontal plane has the lowest value of 6.2° for false killer whales (*Pseudorca crassidens*), and the highest value of 16.5° for harbour porpoises (*Phocoena phocoena*) (*sensu* Koblitz et al., 2012). White-beaked dolphins and *T. aduncus* have a -3-dB beamwidth of 8°. Since the properties of

Table 1A. Sound recordings collected in the pack ice of Baffin Bay in 2012

Recording date	Deployment time/ Local time	Recording duration (min)	Recording depth (m)	GPS position
22 March 2012	1951 – 2020 h	29	100	70 52.884, 54 38.826
22 March 2012	1852 – 1928 h	36	50	70 52.884, 54 38.826
23 March 2012	1425 – 1528 h	63	100	70 57.129, 60 07.957
23 March 2012	1611 – 1630 h	10	50	70 57.129, 60 07.957
24 March 2012	1450 – 1650 h	120	100	70 54.828, 54 39.496
24 March 2012	1558 – 1645 h	47	50	70 54.828, 54 39.496
28 March 2012	1750 – 1810 h	20	100	70 54.859, 56 33.272
29 March 2012	1200 – 1215 h	15	100	70 50.452, 58 55.600
29 March 2012	1354 – 1437 h	43	100	70.59258, 58.926727
29 March 2012	1710 – 1720 h	0	100	70 46.273, 55 59.203
30 March 2012	1215 – 1720 h	305	100	70 43.347, 58 22.633
30 March 2012	1236 – 1415 h	39	100	70 43.347, 58 22.633
31 March 2012	1420 – 1740 h	140	100	70 35.268, 56 16.522
31 March 2012	1435 – 1750 h	135	100	70 35.268, 56 16.522
1 April 2012	1300 – 1440 h	100	100	70.59258, 55.971042
1 April 2012	1315 – 1430 h	69	100	70.59258, 55.971042
1 April 2012	1640 – 1810 h	90	100	70 37.614, 55 42.411
1 April 2012	1702 – 1820 h	0	250	70 37.614, 55 42.411

Table 1B. Sound recordings collected in the pack ice of Baffin Bay in 2013

Recording date	Deployment time/ Local time	Recording duration (min)	Recording depth (m)	GPS position
23 March 2013	1420 – 1452 h	32	100	70.54553 56.12495
29 March 2013	1347 – 1348 h	1	100	70.35978 57.56456

the broadband narwhal clicks are similar to what is described for both white-beaked dolphins and for *T. aduncus*, we could expect a similar beam pattern for narwhals. Recordings using a hydrophone array could verify this. An animation of a click sequence is shown in the supplementary material and can be viewed online. In here, it is possible to see how the frequency contained in the clicks also varies above 150 kHz.

Out of 1,340 min of recordings from both recording systems, we recorded only clicks and no whistles. Sounds from bowhead whales (*Balaena mysticetus*)

Table 2. Information on high-frequency narwhal clicks and click characteristics, including peak frequency, center frequency, 3-dB bandwidth, 10-dB bandwidth, and 90% energy bandwidth

	Peak frequency ± SD (kHz)	Center frequency ± SD (kHz)	3-dB bandwidth ± SD (kHz)	10-dB bandwidth ± SD (kHz)	90% energy bandwidth ± SD (kHz)	90% energy duration ± SD (μs)
High-frequency clicks (N = 300)	69 ± 14	53 ± 13	30 ± 11	52 ± 11	74 ± 13	23 ± 9

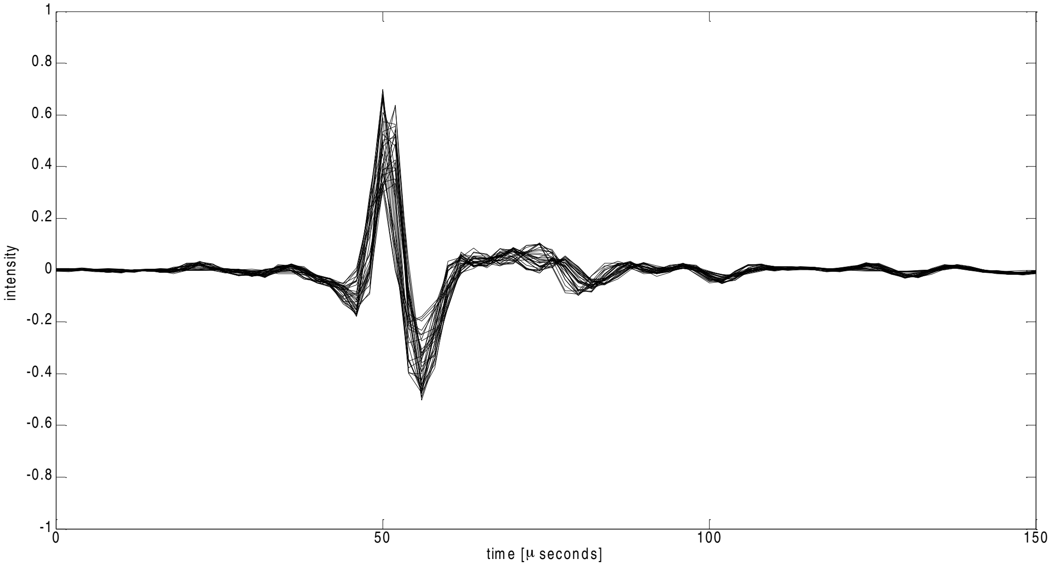

Figure 2. Waveforms of 34 clicks recorded and sampling rate of 500 kHz. These clicks are high amplitude clicks of a click train presumably scanning over the hydrophone.

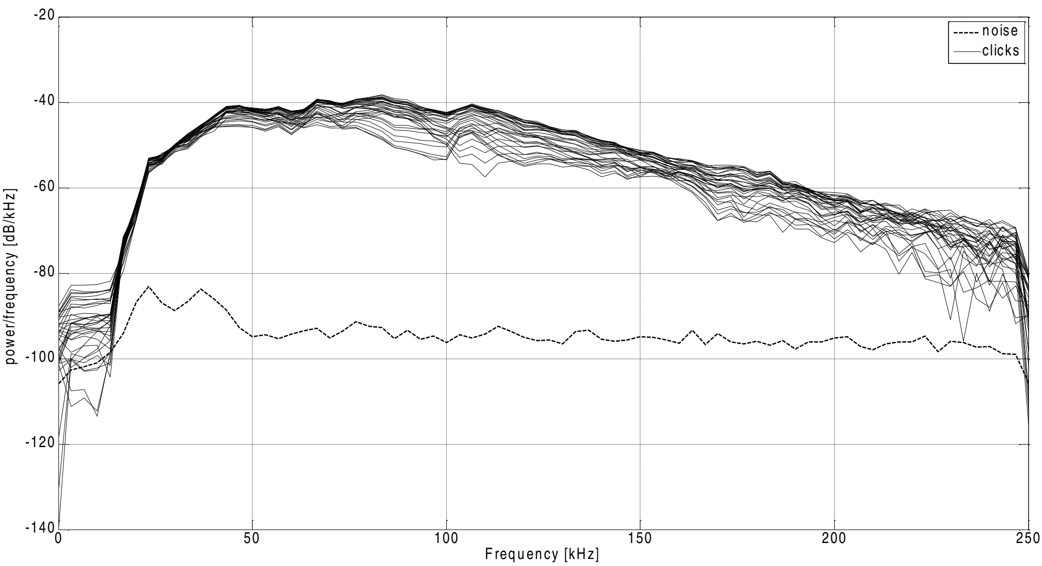

Figure 3. Spectra of 34 clicks recorded (solid lines) and spectra of noise level in the same recording (dashed line); peak frequency is at 66 kHz, but considerable energy extends up to 240 kHz.

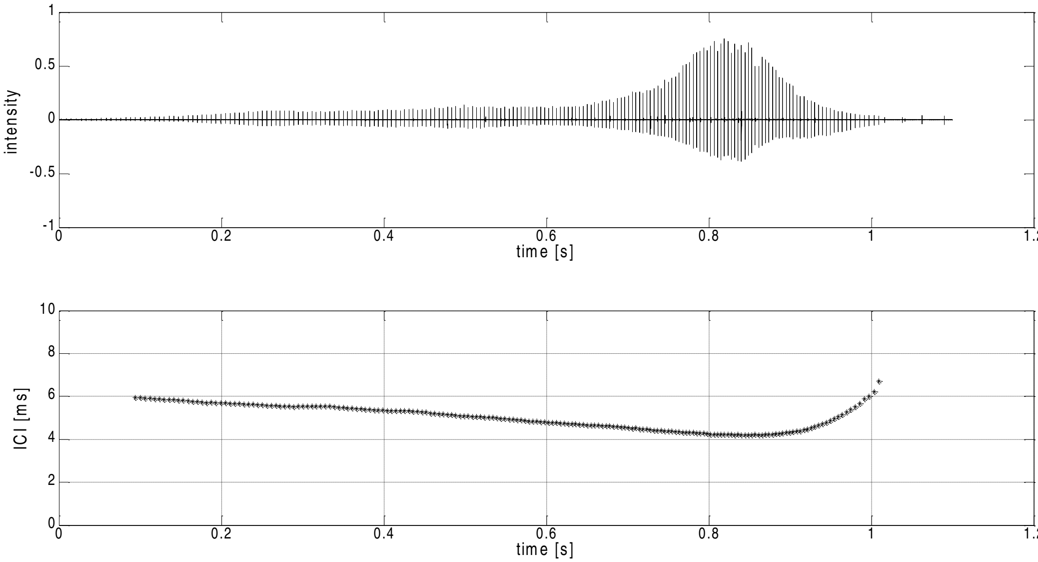

Figure 4. Buzz sequence recorded with the Reson system; the ICI decreases from 6 to a minimum of 4.2 ms.

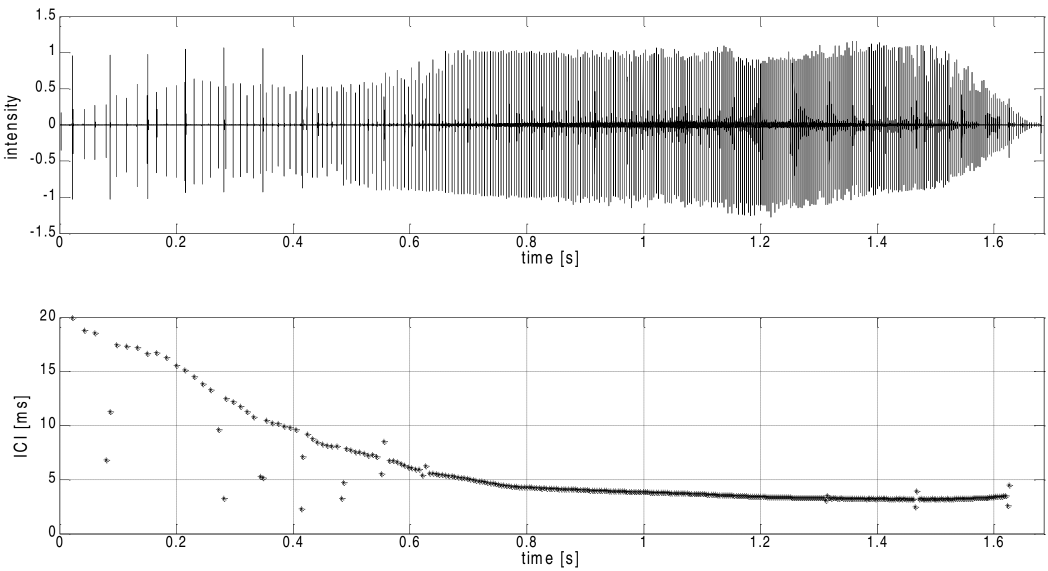

Figure 5. Buzz sequence recorded with the Acousonde™; the ICI decreases from 20 ms to a minimum of 3.2 ms. Clicks from a second animal are recorded at the beginning of this sequence. Notice that some of the clicks are clipped, but this does not change the ICI.

and bearded seals (*Erignathus barbatus*) were also obtained, which meant that low-frequency sounds could be detected. Rasmussen & Miller (2002) reported whistles from white-beaked dolphins when they were socializing (never when they were feeding), and this may be similar in narwhals, although a larger sample size would be needed to be conclusive. In contrast, pilot whales (*Globicephala melas*) have been reported to produce tonal sounds during deep foraging dives (Jensen et al., 2011).

We recorded only a few possible prey capture events (Figures 4 & 5), but this is likely due to the shallow recording depths (above 250 m) as narwhals are known to feed at deep depths (in some cases, > 1,000 m) (Laidre et al., 2003). Prey capture events have been described as decreasing click intervals at a very high repetition rate (often called a buzz). In our study, ICI in the buzz phase is decreasing down to a minimum of 3.2 ms, which is not as short an ICI as 2.5 ms reported by Miller et al. (1995) from narwhals during the summer. The amplitude in the buzz events decreased towards the end of the sequence, which has been shown for other species such as sperm whales (*Physeter macrocephalus*) (Miller et al., 2004), beaked whales (Johnson et al., 2004, 2006; Zimmer et al., 2005) and short-finned pilot whales (*Globicephala macrorhynchus*) (Aguilar de Soto et al., 2008). Studies on prey capture events have been generally conducted on animals in captivity (DeRuiter et al., 2009; Verfuß et al., 2009), while studies on free-ranging animals describing foraging events using acoustic tags have been conducted for various species of toothed whales where acoustic tags can be deployed and retrieved. Johnson et al. (2004) and Madsen et al. (2005) described prey capture events for beaked whales using D-tag data. Possible prey capture events also have been described for free-ranging white-beaked dolphins (Rasmussen et al., 2013), harbour porpoises (Linnenschmidt et al., 2012), and finless porpoises (*Neophocaena phocaenoides*) (Akamatsu et al., 2000, 2005a, 2005b, 2010). Unfortunately, deploying and ultimately retrieving an archival tag in > 98% sea ice concentration during winter precludes collecting these data on the narwhal wintering grounds.

The reason for narwhals making very high-frequency clicks is unknown. However, to date, little is known about what narwhals can hear. Even though white-beaked dolphins make high-frequency clicks (with a second peak at 250 kHz) (Rasmussen & Miller, 2002), they can only hear frequencies up to 180 kHz (Nachtigall et al., 2008). The hearing of a beluga (*Delphinapterus leucas*) was also tested, and it had highly directional hearing for far-field click stimuli similar to that of bottlenose dolphins and more directional than the harbor porpoise (Mooney et al., 2008). This animal was most sensitive at frequencies of 32 and 70 kHz but could hear up to 128 kHz (maximum frequency tested). In another beluga, the animal had its best hearing at 54 kHz and could also hear up to 128 kHz (maximum frequency tested) (Klishin et al., 2000).

However, producing broadband clicks containing high frequencies up to 200 kHz will create echoes from small objects. Even with much lower hearing sensitivity at these high frequencies, it could be an advantage for a narwhal for determining the position of a fish at close range.

In conclusion, we document high-frequency broadband clicks (up to 200 kHz) used by narwhals, and we document buzzes used by narwhals on their wintering grounds. Arctic sea ice has been decreasing in extent and thickness since 1990 (*Arctic Marine Survey Assessment* [*AMSA*] 2009). Model simulations indicate a continuing retreat, and the possibility of ice-free summers in the Arctic Ocean exists within a few decades (Overland & Wang, 2013). These climate-related changes will result in increases to natural resource exploration, marine shipping, transportation and infrastructure, and an overall increase in underwater noise in the Arctic. Furthermore, a growing worldwide demand for natural resources has the Arctic, including waters off both West and East Greenland occupied by narwhals, poised as a significant contributor to the global economy, and offshore seismic exploration activity has begun in many important ecological areas. Understanding baseline use of sound by Arctic cetaceans will be critical for future mitigation of anthropogenic impacts.

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